Dr.-Ing. Wolfgang Sturz
Staatlich geprüfter, öffentlich bestellter
und beeidigter Verhandlungsdolmetscher
und Urkundenübersetzer

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Carl Zeiss, Oberkochen, Gemany

TRANSLATOR'S CERTIFICATE

I, Dr. Wolfgang Sturz, certified, court appointed and sworn translator for the English language hereby certify that the attached translation is, to the best of my knowledge and belief, a true translation of German Patent Application No. 10127227.8.

Signed:

DR.-ING. WOLFGANG STURZ (BDÜ, VVU) • D-72760 REUTLINGEN •
Staatlich geprüfter, öffentlich bestellter und beeidigter
Verhandlungs-dolmetscher und Urkundenübersetzer der englischen und niederländischen Sprache für Baden-Württemberg
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Description

Catadioptric Reduction Lens

The invention relates to a catadioptric projection lens for imaging a pattern arranged in an object plane onto an image plane.

Projection lenses of said type are employed on projection illumination systems, in particular wafer scanners or wafer steppers, used for fabricating semiconductor devices and other types of microdevices and serve to project patterns on photomasks or reticles, hereinafter referred to generically as “masks” or “reticles,” onto an object having a photosensitive coating with ultrahigh-resolution on a reduced scale.

In order create even finer structures, it will be necessary to both increase the numerical aperture (NA) of the projection lens to be involved on its image side and to employ shorter wavelengths, preferably ultraviolet light with wavelengths less than about 260 nm.

However, there are very few materials, in particular, synthetic quartz glass and crystalline fluorides, such as calcium fluoride, magnesium fluoride, barium fluoride, lithium fluoride, lithium calcium aluminum fluoride, lithium strontium aluminum fluoride, and similar, that are sufficiently transparent in that wavelength region available for fabricating the optical elements required. Since the Abbé numbers of those materials that are available lie rather close to one another, it is difficult to provide purely refractive systems that have been sufficiently well-corrected for chromatic aberrations. Although this problem could be solved by employing purely reflective systems, fabricating such mirror systems requires substantial expense and effort.

In view of the aforementioned problems, catadioptric systems that combine refracting and reflecting elements, i.e., in particular, lenses and mirrors, are primarily employed for configuring high-resolution projection lenses of the aforementioned type.

Whenever imaging reflective surfaces are employed, it will be necessary to use beam-deflecting devices if images free of obscurations and vignetting are to be achieved. Both systems having one or more deflecting mirrors and systems having solid beamsplitters are known. Additional plane mirrors may also be employed for folding the optical path. Folding mirrors are usually employed only in order to allow meeting space requirements, in particular, in order to orient the object and image planes parallel to one another. However, folding mirrors are not absolutely necessary from the optical-design standpoint.

Employing systems having a solid beamsplitter in the form of, e.g., a beamsplitter cube (BSC), has the advantage that it allows implementing on-axis systems. Polarization-selective reflective surfaces that either reflect or transmit incident radiation, depending upon its predominant polarization direction, are employed in such cases. The disadvantage of employing such systems is that hardly any suitable transparent materials are available in the desired, large volumes. Moreover, fabricating optically active beamsplitter coatings situated within beamsplitter cubes is extremely difficult. Heating effects occurring within beamsplitters may also present problems at high radiant intensities, since inside the beamsplitters an intermediate image is created.

One example of such a system is depicted in European Pat. No. EP-A-0 475 020, which corresponds to U.S. Pat. No. US-A-5,052,763, where the mask involved lies directly on a beamsplitter cube and the intermediate image formed lies within the beamsplitter cube, behind its internal beamsplitting surface. Another example is depicted in U.S. Pat. No. US-A-5,808, 805 and the associated application for continuation of same, US-A-5,999,333, where a multi-element compound-lens group with a positive refractive power lies between the object plane and a beamsplitter cube. The collected light beam is initially deflected toward a concave mirror by the beamsplitter cube and then reflected back to the beamsplitter cube and through its beamsplitting surface toward the aforementioned compound-lens group with a positive refractive power by the concave mirror. The intermediate image lies within the beamsplitter cube, in the immediate vicinity of its beamsplitting surface. However, none of these documents makes any statements regarding heating problems that might arise or how they may be avoided.

European Patent No. EP-A-0 887 708 states measures for avoiding thermally induced imaging errors for a catadioptric system having a beamsplitter cube, but apparently no intermediate image falling within its beamsplitter cube. The intention here was obtaining a symmetric distribution of radiant intensity over the beamsplitter cube's beamsplitting surface, i.e., a distribution that would yield a heating profile symmetrically distributed over the beamsplitter's beamsplitting surface, by suitably routing the beam transiting the beamsplitter cube. It was stated that the resultant wavefront distortions, such as those that result from nonuniform heating, which are difficult to eliminate, were avoidable.

Some of these disadvantages of systems having beamsplitter cubes may be avoided in the case of systems having one or more deflecting mirrors in their beam-deflecting device. However, such systems have the disadvantage that they are, by virtue of their design, necessarily off-axis systems.

A catadioptric reduction lens of that type is described in European Pat. No. EP-A-0 989 434, which corresponds to U.S. Serial No. 09/364382. These types of lenses have a catadioptric first section having a concave mirror and a beam-deflection device that is followed by a dioptric second section arranged between their object plane and their image plane. Their beam-deflecting device, which is configured in the form of a reflecting prism, has a first reflective surface for deflecting radiation coming from their object plane to a concave mirror and a second reflective surface for deflecting radiation reflected by that concave mirror to a second section containing exclusively refractive elements. Their catadioptric first section creates a real intermediate image that lies slightly behind this prism's second reflective surface and well ahead of the first lens of their second section. Their intermediate image is thus readily accessible, which may be taken advantage of for, e.g., installing a field stop.

Another reduction lens that has a beam-deflection device having a deflecting mirror is described in U.S. Pat. No. US-A-5,969,882, which corresponds to European Pat. No. EP-A-0 869 383. This system's deflecting mirror is arranged such that light coming from its object plane initially strikes the concave mirror of its first section, where it is reflected to the system's beam-deflecting device's deflecting mirror, where

it is reflected to a second reflective surface, where it is deflected toward the lens of the system's exclusively dioptric second section. The elements of this system's first section that are utilized for creating its intermediate image are configured such that its intermediate image lies close to its beam-deflecting device's deflecting mirror. Its second section refocuses its intermediate image onto its image plane, which may be oriented parallel to its object plane, thanks to the reflecting surface that follows its intermediate image in the optical train.

U.S. Pat. No. US-A-6,157,498 depicts a similar configuration whose intermediate image lies on, or near, the reflective surface of its beam-deflecting device. Several lenses of its second section are arranged between its beam-deflecting device and a deflecting mirror located in its second section. In addition, an aspheric surface is arranged in the immediate vicinity of, or near to, its intermediate image exclusively for the purpose of correcting for distortions, without affecting other imaging errors.

A projection lens having a reducing catadioptric section and an intermediate image in the vicinity of the deflecting mirror of a beam-deflection device is depicted in German Pat. No. DE 197 26 058.

The U.S. patent mentioned above, U.S. Pat. No. US-A-5,999,333, depicts another catadioptric reduction lens having deflecting mirrors for which light coming from its object plane initially strikes a concave mirror, where it is reflected to the lens' beam-deflecting device's sole reflective surface. The intermediate image created by its catadioptric section lies close to this reflective surface, which reflects light coming from that concave mirror to a dioptric second section that images this intermediate image onto its image plane. Both its catadioptric section and its dioptric section create reduced images.

A similarly configured lens for which the intermediate image created by its catadioptric section lies near its deflecting device's sole reflective surface is depicted in Japanese Pat. No. JP-A-10010429. The surface of the lens of the following dioptric section that lies closest to the deflecting mirror is aspheric in order that it may make a particularly effective contribution to correcting for distortions.

Those systems whose intermediate image lies near, or on, a reflective surface may be compactly designed. They also allows keeping the field curvatures of these systems, which are off-axis illuminated, that will need to be corrected small. One of their disadvantages is that even the slightest flaws on any of their reflective surfaces may adversely affect the qualities of images projected onto their image plane. Moreover, their focusing of radiant energy onto reflective surfaces may cause heating effects that might adversely affect their imaging performance. The resultant, locally high, radiant intensities may also damage the reflective coatings that are normally applied to the surfaces of mirror blanks.

The problem addressed by the invention is avoiding the disadvantages of the state of the art. In particular, a projection lens whose imaging performance will be relatively insensitive to fabrication tolerances is to be devised.

To solve this problem, the invention proposes a catadioptric projection lens having the characteristics set out in claim 1. Beneficial embodiments thereon are stated in the dependent claims. The wording appearing in all of said claims is herewith made a part of the contents of this description.

A projection lens in the sense of the invention that is of the type mentioned at the outset hereof will be characterized in that its second, dioptric section, which starts behind the final reflective surface of its beam-deflecting device, has at least one lens arranged between said final reflective surface and its intermediate image. Said intermediate image thus lies within its second, exclusively refractive, section in order that at least one of the lenses of said second section that precede said intermediate image in the optical train may contribute to creating said intermediate image. The invention thus foresees that the distance between said final reflective surface of said beam-deflecting device and said intermediate image will be considerable, which may allow, e.g., creating an accessible intermediate image in order to, e.g., allow installing a field stop in order to reduce stray-light levels. It will be particularly beneficial if that large distance will provide that said final reflective surface lies in a zone where the beam diameter is rather large, which will provide for its uniform illumination while avoiding hazardous, localized, peaks in radiant intensity and spread any heating of the optical element to which said reflective surface has been

applied over a larger area, which will, in turn, improve its imaging performance. More important, however, is that any minor flaws that may be present on its reflective surface will have only a negligible, or no, effect on the qualities of images projected onto the image plane. Lenses with high imaging performance may thus be constructed, in spite of the minimal demands on the uniformity and figure of said final reflective surface.

The term "final reflective surface," as used here, is to be interpreted as referring to that reflective surface that lies immediately ahead of said intermediate image in the optical train, where said surface may be a polarization-selective beamsplitting surface of a beamsplitter cube (BSC) or the surface of a highly reflective deflecting mirror, which may be preceded by another deflecting mirror of a beam-deflecting device in the optical train. Rear-surface mirrors in the form of deflecting prisms are also feasible. In the case of projection lenses according to the invention, said "final reflective surface" concludes their catadioptric section. Said final reflective surface may be followed by another reflective surface that causes a beneficial, from the structural standpoint, folding of said projection lens' optical path that has been added at the entrance to, or between the lenses of, said section in order to, e.g., allow orienting said projection lens' object and image planes parallel to one another.

Said optical element between said final reflective surface and said intermediate image that has been termed a "lens" here may also differ from conventional lenses in form and function and may be in the form of, e.g., a planar plate having an aspheric correction, a truncated lens, or a half-lens. The term "lens," as used here, thus, in general, refers to any transparent optical medium that optically affects transmitted radiation.

The aforementioned benefits apply regardless of whether a lens is arranged between said final reflective surface and said real intermediate image, largely due to the large distance between same. Said distance, which shall hereinafter also be referred to as the "intermediate-image distance," should preferably be chosen such that the diameter of the beam at a surface orthogonal to said optical axis at the intersection of said final reflective surface with said optical axis will be at least 10 % of the diameter of said concave mirror, e.g., 17 % or more of said diameter. However, said

distance should not be so large that said ratio of the diameter of said beam to the diameter of said concave mirror will be much greater than 20 % or 25 % in order to confine the field curvatures that will need to be corrected to manageable levels. Said large intermediate-image distance will allow arranging said at least one lens between said final reflective surface and said real intermediate image, where said lens or lenses will preferably have a positive refractive power or powers, which will keep the diameter of those lenses that follow said intermediate image small, which, in turn, will allow designing said second section in manners that will allow reducing the quantities of materials required.

Arranging at least one lens between said final reflective surface and said real intermediate image also provides hitherto unknown opportunities for minimizing, or totally eliminating, the deleterious effects of lens heating. In order to reduce or preclude same, a preferred embodiment of the invention has a front intermediate-image lens arranged on its object side, ahead of said intermediate image, and a rear intermediate-image lens arranged on its image side, behind said intermediate image, where said intermediate-image lenses are symmetrically arranged with respect to said intermediate image such that any asymmetric contributions to imaging errors, such as coma, caused by heating of said intermediate-image lenses will be partially compensated, even nearly fully compensated, as shall be discussed in greater detail in terms of the sample embodiments to be discussed below.

The aforementioned symmetric arrangement of said front and rear intermediate-image lenses employed for partially or fully compensating for the effects of asymmetric heating of lenses situated in the vicinity of said intermediate image will be beneficial for both projection lenses of said type and other optical imaging systems that create at least one real intermediate image.

Obtaining the favorable arrangement of said intermediate image according to the invention will be simplified if said first, catadioptric section does not contribute, or does not materially contribute, to the overall reduction ratio of said projection lens. Said catadioptric first section of said projection lens should preferably have a magnifications, β_M, that exceed 0.95 and preferred embodiments of same will have

magnifications of $\beta_M > 1$, i.e., will create enlarged intermediate images, which will facilitate shifting same to said refractive second section.

In order to keep the field curvatures that will need to be corrected small in spite of said favorable arrangement of said intermediate image, it will be preferable to provide means for correcting for spherical aberration produced by said first section, which, in turn, will provide that the axial locations of its paraxial intermediate image and the intermediate image created by outlying marginal rays will be shifted such that they are closer proximity with respect to one another. It will be beneficial if the longitudinal spherical aberration, SAL, produced by said first section satisfies the condition $0 < |SAL/L| < 0.025$, where L is the geometric distance between said object plane and the image plane of same, as shall be discussed in greater detail below.

Preferred embodiments of the invention will provide that that surface of that lens of said refractive section that lies closest to said intermediate image will be spherical. However, the surfaces of both lenses facing said intermediate image might also be spherical, which will allow fabricating lenses with high imaging performances and low scatter in their imaging performances without need for imposing extremely stringent tolerances on same, since the figuring accuracies attainable during fabrication are generally better for spherical surfaces than for aspherical surfaces, which also may exhibit transmittance gradients and excessive surface microroughnesses. On the other hand, those surfaces in the vicinity of intermediate images have extremely strongly impacts on corrections for imaging errors, such as distortion, which is why conventional lens designs frequently employ aspherical surfaces near intermediate images. However, in the case of those projection lenses considered here, it will be preferable to employ lenses with high-precision, nearly perfectly accurately figurable, spherical surfaces in the vicinity of said intermediate image.

The previous and other properties can be seen not only in the claims but also in the description and the drawings, wherein the individual characteristics may be used either alone or in sub-combinations as an embodiment of the invention and in other areas and may individually represent advantageous and patentable embodiments. It is shown in:

Fig. 1 a longitudinal sectional drawing of a first embodiment of the invention,

Fig. 2 a longitudinal sectional drawing of a second embodiment of the invention,

Fig. 3 an enlarged view of the vicinity of the beam-deflection device depicted in Fig. 1,

Fig. 4 a longitudinal sectional drawing of another embodiment of the invention that has optical characteristics corresponding to those of the embodiment depicted in Fig. 1 and a folded second section, and

Fig. 5 an embodiment of a microlithographic projection illumination system according to the invention.

In the following description of preferred embodiments of the invention, the term "optical axis" refers to a straight line or a sequent of straight-line segments passing through the centers of curvature of the optical elements involved, where said optical axis will be folded at the reflective surfaces of deflecting mirrors or other reflective optical elements. Directions and distances shall be designated as "image-side" directions or distances if they are directed toward either the image plane involved or a substrate to be illuminated that is present in said plane and as "object-side" directions or distances if they are directed along that segment of said optical axis extending toward the object involved. In the case of those examples presented here, said object may be either a mask (reticle) bearing the pattern of an integrated circuit or some other pattern, such as a grating. In the case of those examples presented here, the image of said object is projected onto a wafer coated with a layer of photoresist that serves as said substrate, although other types of substrate, such as components of liquid-crystal displays or substrates for optical gratings, may also be involved. In the following, identical or equivalent features of the various embodiments of the invention will be assigned the same reference numbers for greater clarity.

A typical design for a catadioptric reduction lens (1) based on a first embodiment of same is depicted in Fig. 1 and serves to project a reduced image, e.g., an image

whose linear dimensions have been reduced by a factor of 1/4, of a pattern on a reticle or similar that is arranged in an object plane (2) onto an image plane (4) while creating a single, real, intermediate image (3). Said lens (1) has a catadioptric first section (5) containing a concave mirror (6) and a beam-deflecting device (7) arranged between its object plane (2) and image plane (3) and a dioptric second section (8) that contains exclusively refractive optical elements following said beam-deflecting device. Said beam-deflecting device (7) is configured in the form of a reflecting prism and has a first, planar, reflective surface (9) for deflecting radiation coming from said object plane (2) toward said concave mirror and a second, planar, reflective surface (10) for deflecting radiation reflected by said imaging concave mirror (6) toward said second section (8). Said reflective surface (10) represents both the final reflective surface of said catadioptric section (5) and the final reflective surface of said beam-deflecting device (7). Although said first reflective surface (9) for deflecting radiation to said concave mirror (6) is necessary, said second reflective surface (10) may be deleted, in which case, said object plane and said image plane would be roughly orthogonal to one another if no other deflecting mirrors were employed. As may be seen from Fig. 4, the optical train may also be folded within the bounds of said refractive section.

As may be seen from Fig. 1, light from an illumination system (not shown) enters a projection lens from that side of said object plane (2) opposite to said image plane and initially passes through a mask arranged in said object plane. Light transmitted by said mask then transits a collecting lens (11) with a convex entrance surface, where said collecting lens is arranged between said object plane (2) and said beam-deflecting device (7), and then is deflected toward a mirror group (12) that contains both said concave mirror (6) and a pair of negative lenses (13, 14) situated immediately in front of same, each of which has its surfaces curved towards the front surface of said concave mirror (6), by the folding mirror (9) of said beam-deflecting device (7), where said folding mirror (9) is inclined at an angle with respect to the optical axis (15) of the preceding section differing from 45° that has been chosen such that it deflects light incident on it through an angle greater than 90°, e.g., through 100°. Light reflected by said concave mirror (6) that has passed through said pair of negative lenses (13, 14) twice and been reflected back to said beam-deflecting device (7) will be reflected toward said dioptric second section (8) by the

second folding mirror (10) of said beam-deflecting device (7). The optical axis (16) of said second section is parallel to the optical axis (15) of said entrance section and thus allows a mutually parallel orientation of said object plane (2) and said image plane (3), which will simplify the operation of a scanner.

A special characteristic of said second section (8) is that said second folding mirror (10) is followed at a distance by a first lens (17), which, in the case of the example shown, is in the form of a biconcave positive lens whose positive refractive power contributes to the creation of said real intermediate image (3). In the case of the embodiment depicted, said intermediate image will lie on the image side, following said first lens (17) and at a distance from same, whereby a paraxial intermediate image, which has been indicated by a pseudoplane (18), lying closer to the spherical exit surface of said first lens (17) than the intermediate image (19) created by outlying marginal rays.

A rear lens group (20) of said second section (8) that follows said intermediate image (3) images said intermediate image (3) onto said image plane (4). That lens (21) of said group (20) that lies closest to said intermediate image (3) is in the form of a positive meniscus lens whose curved surfaces are curved toward said object plane and whose distance from said intermediate image (3) exceeds the distance between said intermediate image and said first lens (17) of said second section (8). Said lens (21) is followed by another positive meniscus lens (22) whose curved surfaces are also curved toward said object plane and is arranged at a large distance from same that, in turn, is followed by a curved meniscus lens (23) whose curved surfaces are curved toward said object plane, a biconcave negative lens (24), and a biconvex positive lens (25) arranged at axial distances from same. Said lenses are followed by a positive meniscus lens (26) whose curved surfaces are curved toward said object plane and that has a slightly negative refractive power, which, in turn, is followed by a biconvex positive lens (27). A meniscus-shaped air space (37) whose curved surfaces are curved toward said object plane is situated between these latter lenses (26, 27). Another meniscus lens (28), which has a positive refractive power and whose curved surfaces are also curved toward said object plane, that follows said lenses in the optical train is immediately followed by a readily accessible system stop (29) arranged such that said air space (37) in the vicinity of said stop (29) lies ahead

of same in the optical train. Said stop (29) is followed by a negative meniscus lens (30) whose concave surface faces said image plane that, in turn, is followed by a biconvex positive lens (31), a meniscus lens (32) that has a positive refractive power and whose curved surface is curved toward said object plane, a thick, biconvex positive lens (33), and another, small-diameter, biconvex, positive lens (34) that focus the transmitted beam and direct it toward a wafer arranged in said object plane (4). The optical element closest to said wafer is a plane-parallel end plate (35).

Table 1 summarizes the design specifications involved in tabular form, where the leftmost column thereof lists the number of the refractive, reflective, or otherwise designated surface, F, involved, the second column thereof lists the radius , r, of said surface [mm], the third column thereof lists the distance, d, between the surface involved and the next surface [mm], a parameter that is referred to therein as the "thickness", and the fourth column thereof lists the refractive index of the material employed for fabricating the optical element following the entrance face, a parameter that is referred to therein as its "index." The fifth column of said table is used for designating reflective surfaces, which are identified by the legend "REFL." The overall length, L, of the lens involved, measured from its object plane to its image plane, is about 1,250 mm.

In the case of this particular embodiment, eight of its surfaces are aspherical, namely the surface F7 and the surfaces F13, F20, F22, F29, F30, F36, F39, and F45. In the figures, aspherical surfaces are hatched. Table 2 lists the associated data for these aspherical surfaces, from which they may be computed using the following equation:

$$p(h) = [((1/r)h^2)/(1 + SQRT(1 - (1 + K)(1/r)^2h^2)] + C1\cdot h^4 - C2\cdot h^6 + \ldots ,$$

where r is their local radius of curvature and h is the distance of a point on their surface from their optical axis. p(h) thus represents the radial displacement of said point from the inflection point of the surface in question along the z-direction, i.e., along their optical axis. The constants K, C1, C2, etc., are listed in Table 2.

The optical system (1) that may be reproduced using these data has been designed for use at a working wavelength of about 157 nm, at which the calcium fluoride employed for fabricating all of the lenses involved has a refractive index, n, of 1.55841. Its image-side numerical aperture, NA, is 0.80. Said system has been designed to have a field measuring 22 mm x 7 mm and is doubly telecentric.

The operation of said optical system and several of its beneficial features will be described in greater detail below. The weakly positive first lens (11) of its catadioptric section (5) has a focal length that is roughly equal to the distance to same's concave mirror (6). Said concave mirror thus lies in the vicinity of a pupil of the system and may have a relatively small diameter, which will simplify its fabrication. The folding of the optical path at said section's first deflecting mirror (9) through an angle exceeding 90° is beneficial in that it provides a large working distance over the lens' full width. The pair of negative meniscus lenses (13, 14) immediately preceding said concave mirror (6) correct for longitudinal chromatic aberration, CHL. In the case of this particular embodiment, it will be beneficial if only two lenses (13, 14) are arranged within that portion of said catadioptric section (5) that is transited twice, since every lens situated within said portion has a double effect on, e.g., transmittance and the wavefront distortions, without providing any additional leeway for correcting for same.

A feature that is particularly noteworthy is that said catadioptric section (5), whose final optically effective surface is a deflecting mirror (10), either does not contribute to the system's overall reduction ratio or makes only a minor contribution thereto. Said catadioptric section has, in the embodiment shown here, a magnification, β_M, given by $|\beta_M| = 0.99$, which makes a major contribution to the fact that the system's intermediate image (3) will be created at a great distance (the intermediate-image distance) down the optical train from said final deflecting mirror (10), which yields another benefit in that said the radiant intensity incident on second deflecting mirror (10) will be relatively uniformly distributed over a larger area than that represented by the state of the art, which, in turn, means that imaging errors due to nonuniform heating in the vicinity of said deflecting mirror (10) or the system's beam-deflecting device (7) will either be reduced or avoided altogether. Said intermediate-image

distance has been chosen here such that the diameter of the beam incident on a surface normal to the optical axis (16) at the point where said second deflecting mirror (10) intersects said optical axis will range from about 17 % to about 18 % of the diameter of said main concave mirror (6).

Since said intermediate image will not lie on, or in the immediate vicinity of, said deflecting mirror (10), minor errors in fabricating the reflective surface of said deflecting mirror (10) may be readily tolerated, since they will either not be imaged onto the system's object plane (4) or will be defocused there and thus will have no adverse effects on images projected onto a wafer arranged on said object plane (4). Since said final reflecting surface (10) is subjected to relatively uniformly distributed radiant intensities only and minor errors in same are tolerable, it may be expected that the imaging performance of said projection lens (1) will remain unaffected by degradation of the (coated) surface of said mirror (10), even after many years of service in continuous operation.

The axial distance between said final reflecting surface (10) of said catadioptric section (5) and said intermediate image (3) that follows same in the optical train will, in the case of the embodiment depicted, as well as in all other embodiments of the invention, be so large that at least one lens of the dioptric section (8) that follows said catadioptric section in the optical train may be arranged between said final reflecting surface (10) and said intermediate image (3). In the case of the sample embodiment depicted, said lens is a biconvex lens (17) whose positive refractive power contributes to creation of said intermediate image (3). Incorporating sufficiently high refractive power into the region between said mirror (10) and said intermediate image will allow keeping the diameters of those lenses that follow said intermediate image (3) in the optical train small, which, in turn, will facilitate designing said dioptric section such that the quantities of materials required for its fabrication will be reduced. One opportunity for realizing said savings of materials will arise if said first lens (17) is fabricated in the form of a half-lens, which will be possible here, since only around half of its surface is optically utilized.

The invention allows optimizing catadioptric projection lenses having at least one intermediate image in relation to the adverse effects of asymmetric lens heating by

adapting those lenses (17, 21) that surround their intermediate image to suit one another in an appropriate, special manner. Said first lens (17) located on their object side, ahead of said intermediate image (3), is also termed a "front intermediate-image lens," while said meniscus lens (21) that follows said intermediate image is also termed a "rear intermediate-image lens." Said intermediate-image lenses (17, 21) should be symmetrically arranged with respect to said intermediate image (3) such that contributions to imaging errors, such as coma, due to heating of said lenses will be partially compensated or largely fully compensated, where the first of said intermediate-image lenses (17) may, so to speak, provide a preliminary grip on thermally induced imaging errors that will be compensated by the second of said intermediate-image lenses (21) that follows it in the optical train, which will also be subject to heating. In the case of those off-axis systems that have been described here in terms of examples, those lenses situated in the vicinity of said intermediate image (3) will be extremely asymmetrically illuminated, which will lead to same being subjected to highly asymmetric heating effects. Said effects are largely responsible for uncorrectable distortions and coma occurring in images projected onto wafers. However, it should be noted at this juncture that imaging errors due to lens heating may limit imaging performance in the case of those catadioptric systems that have been described here in terms of examples.

If said lenses (17, 21) are symmetrically arranged about said intermediate image (3) in the manner described above, then it may be arranged that, e.g., the height ratios, i.e., the distances from the optical axis (16), of the upper and lower marginal rays of the field beams at said front and rear intermediate-image lenses (17, 21) will just barely reverse, which will allow using said rear intermediate-image lens (21) to partially or fully compensate for effects due to asymmetric heating of said front intermediate-image lens (17).

The symmetry mentioned above in relation to compensating for asymmetric lens-heating effects will not usually be equivalent to any geometric symmetries, e.g., symmetry with respect to reflection in the plane of said intermediate image (3), which will be clear from the layout of the embodiment depicted in Fig. 1, for which the distance between its intermediate image and the spherical exit surface of said front

intermediate-image lens (17) is less than the distance between same and the aspherical entrance surface of said rear intermediate-image lens (21).

Among those lenses (17 - 35) situated within said second section (8), only those situated within its rearward lens group (20), i.e., all of said lenses, with the lone exception of lens (17), contribute to imaging said intermediate image onto the plane (4) of said wafer. Said lenses have been combined in a manner suitable for correcting for imaging errors in said intermediate image to the extent that a sufficient adequate correction status will be obtained at the plane (4) of said wafer. Among those lenses situated within said rearward lens group (20), lens (21) closest to the intermediate image plays a special role in same, since any imaging errors due to asymmetric heating of said lens will be at least partially compensated by said lens (17) situated ahead of said intermediate image, which provides a preliminary grip on thermally induced distortions, which will be eliminated upon transmission through said rear intermediate-image lens (21).

Fig. 2 depicts a sectional view of another embodiment whose detailed specifications (data defining its aspherical surfaces) appear in Tables 3 and 4. This particular reduction lens (1), which has also been designed for a working wavelength of about 157 nm, has a basic layout similar to that of the embodiment depicted in Fig. 1 and also has a numerical aperture, NA, of 0.80. The reference numbers employed here are identical to those assigned to the corresponding lenses or lens groups appearing in Fig. 1. However, one major difference between this design and that of Fig. 1 is that an intermediate group (41) of lenses comprising a biconvex positive lens (42) facing its beamsplitter (7) and a biconcave negative lens (43) facing a mirror group (12), has been arranged within that portion of its optical train that is transited twice, roughly midway between said beamsplitter (7) and said mirror group (12). Increasing the refractive power of said intermediate lens group (41) may beneficially affect the diameter of said mirror group (12), which may then be reduced. In addition to said rear intermediate-image lens (21), a negative lens (44) has been arranged in the vicinity of its intermediate image.

Unlike the embodiment depicted in Fig. 1, both the exit surface of said front intermediate-image lens (17) facing said intermediate image (3) and the convex

entrance surface of said rear intermediate-image lens (21) facing said object plane are spherical, which will allow highly accurately figuring both of these surfaces situated near said intermediate image, which, in turn, will allow minimizing imaging errors due to fabrication errors, such as surface irregularities or residual microroughness.

In the case of embodiments according to the invention, minor longitudinal spherical aberration (SAL) at said intermediate image may be beneficial. In the case of the typical overall length, L, of about 1,250 mm involved here, SAL should not be more than about 30 mm, or at most 20 mm, in order that the ratio SAL/L will not be much greater than about 0.025. Under such conditions, the field curvatures that will need to be corrected may be kept small, in spite of the large intermediate-image distance involved, as will now be discussed in greater detail based on Fig. 3, which schematically depicts the vicinity of the beamsplitter prism (7) depicted in Fig. 1, where said front intermediate-image lens (17) has been schematically depicted only. The solid line designates a beam (45) close to the optical axis coming from a concave mirror, where, in the case of low SAL, said beam will create a marginal-ray intermediate image (46) in the plane (18) of the paraxial intermediate image. Said beam is routed such that that marginal ray (47) closest to said optical axis (16) will just barely fully strike the second surface (10) of said beamsplitter prism in order to provide imaging that will be free of vignetting. In the case of larger SAL, imaging that will be free of vignetting will only be attainable under otherwise identical conditions if the object field (48), and thus its associated intermediate image (46'), shifts said beam further away from said optical axis (16), as indicated by the dotted line designating said shifted beam (45'), whose marginal-ray intermediate image (46') will be formed behind said plane (18) of said paraxial intermediate image and at a certain distance from same. The location of said marginal ray (47) closest to said optical axis (16) will remain virtually unaltered compared to the case of said beam (45), while the location of that marginal ray (49) farthest away from said optical axis will have moved further away from same, provided that the beam divergence remains constant. It may be seen that the distance between said intermediate image (46) and said optical axis (16), i.e., the distance between the plane (18) of said paraxial intermediate image and said marginal-ray intermediate image (46), will be reduced in step with reductions in SAL. Similar will apply to the location of the object

field, which is why low spherical aberrations help keep the field curvatures that will need to be corrected small.

Numerous variations on the invention, none of which have been illustrated here, are feasible. For example, said folding mirrors (9, 10) of said beam-deflecting device (7) may be replaced by separate folding mirrors having another orientation, if necessary. In the case of lenses with low numerical apertures and/or lenses with a side arm housing their main mirror (6) that is roughly normal to the structure housing the remainder of their optical elements, high-reflectance surfaces on the inner surfaces of, e.g., a deflecting prism, may be employed instead of mirrors with reflective coatings. Said beam-deflecting device (7) equipped with a pair of high-reflectance deflecting mirrors (9, 10) may also be replaced by a solid beamsplitter, such as a beamsplitter cube having a single beamsplitting surface that partially reflects and partially transmits incident radiation. Same might also be replaced by a partially transmitting mirror, although a polarization beamsplitter would be preferable. The reflective surface involved would represent the final reflective surface ahead of said intermediate image.

Another opportunity for configuring a projection lens according to the invention is depicted in Fig. 4. Although the basic layout, i.e., the types of lenses involved, their numbers, their radii of curvature, the air spaces involved, etc., of the projection lens (1) depicted therein is identical to that of the embodiment depicted in Fig. 1 (cf. Tables 1 and 2), the beam-deflecting device (7), which is needed due to the type of layout involved, employed here has just a single, planar deflecting mirror (9). A second deflecting mirror (10) has been arranged between the relatively widely spaced lenses (21, 22) within its second, dioptric section (8), behind its intermediate image (3) in the optical train, in order to obtain a parallel orientation of the plane (2) of said reticle and the plane (4) of said wafer for this type of layout as well. Since said deflecting mirror (10) has been arranged behind said intermediate image (3), it does not form part of said beam-deflecting device (7), whose final reflective surface will now be said deflecting mirror (9). In the case of this type of design, light coming from said object plane (2) initially strikes an imaging concave mirror (6) that reflects it toward said sole deflecting mirror (9) of said beam-deflection device (7). The convergent beam incident on said final deflecting mirror (9) is deflected to said

second, dioptric section (8), which is bent at a right angle due to its integral deflecting mirror (10). A lens (17) of said second section is arranged between said deflecting mirror (9) and said intermediate image (3), which is situated far from said deflecting mirror, exactly as in the case of the other embodiments. All of the benefits of the embodiment depicted in Fig. 1 are retained.

In the case of those embodiments described here, all of their transparent optical components are fabricated from the same material, namely, calcium fluoride. However, other materials, in particular, those crystalline fluoride materials mentioned at the outset hereof, that are transparent at the working wavelength to be involved may also be employed. At least one other material may also be employed in order to, e.g., correct for chromatic aberration, if necessary. The benefits of the invention may, of course, also be applied to systems intended for use at other working wavelengths, e.g., 248 nm or 193 nm, falling within the ultraviolet spectral region. Since, in the case of those embodiments depicted here, a single material is employed for fabricating all of their lenses, adapting the designs that have been illustrated to use at other wavelengths will be a simple matter for optical specialists. Other lens materials, such as synthetic quartz glass may be employed for fabricating some or all of their optical elements, particularly in the case of systems intended for use at longer wavelengths.

Projection lenses according to the invention may be employed on any suitable microlithographic projection illumination system, e.g., on wafer steppers or wafer scanners. Fig. 4 schematically depicts a wafer scanner (50) comprising a laser light source (51) equipped with an associated device (52) for narrowing its band width. An illumination system (53) generates a large, sharply defined, highly uniformly illuminated, image field that has been adapted to suit the telecentricity requirements of the projection lens (1) that follows it in the optical train. Said illumination system (53) is equipped with devices for selecting an illumination mode and may be switched between, e.g., conventional illumination with a high degree of coherence, annular illumination, and dipole or quadrupole illumination. Said illumination system is followed by a device (54) for holding and manipulating a mask (55) such that said mask (55) lies in said image plane (2) of said projection lens (1) and may be translated over said plane when said system is operated in scanner mode. In the

case of the wafer scanner depicted here, said device (54) thus incorporates the scanner drive for said mask.

Said plane (2) of said mask is followed by said projection lens (1) that projects a reduced image of said mask onto a wafer (56) coated with a layer of photoresist that has been arranged in the image plane (4) of said projection lens (1). Said wafer (56) is held in place by a device (57) that includes a scanner drive in order to allow translating said wafer in synchronism with said mask. All of said systems are controlled by a controller (58). The designs of such systems are known and will thus not be discussed any further here.

Table 1

Surface no.	Radius	Thickness	Index	Reflective
0	0,0000	36,000	1	
1	0,0000	0,000	1	
2	303,9247	22,169	1,55841	
3	2732,7256	96,271	1	
4	0,0000	0,000	-1	REFL
5	0,0000	-468,173	-1	
6	199,7080	-10,268	-1,55841	
7	485,9116	-25,206	-1	
8	186,8130	-10,064	-1,55841	
9	448,8758	-19,609	-1	
10	243,7460	19,609	1	REFL
11	448,8758	10,064	1,55841	
12	186,8130	25,206	1	
13	485,9116	10,268	1,55841	
14	199,7080	469,450	1	
15	0,0000	0,000	-1	REFL
16	0,0000	-100,166	-1	
17	-532,8260	-25,379	-1,55841	
18	635,9179	-10,000	-1	
19	0,0000	-115,933	-1	
20	-311,6936	-24,721	-1,55841	
21	-729,4902	-219,394	-1	
22	-276,2460	-15,427	-1,55841	
23	-448,8506	-75,934	-1	
24	-158,3810	-30,587	-1,55841	
25	-163,4782	-40,576	-1	
26	419,7809	-20,540	-1,55841	
27	-237,0092	-32,234	-1	
28	-428,0516	-30,182	-1,55841	
29	693,3900	-23,874	-1	
30	-241,2068	-10,000	-1,55841	
31	-182,4638	-25,712	-1	
32	-422,9386	-36,706	-1,55841	
33	327,0334	-7,823	-1	
34	-150,5655	-28,311	-1,55841	
35	-314,2186	-15,947	-1	
36	0,0000	-3,484	-1	
37	-172,8501	-12,272	-1,55841	
38	-116,0764	-25,993	-1	
39	-230,6308	-32,436	-1,55841	
40	465,5346	-4,280	-1	
41	-153,0332	-30,802	-1,55841	
42	-514,5406	-8,487	-1	
43	-157,6109	-41,061	-1,55841	
44	2904,8207	-4,477	-1	
45	-226,8988	-24,123	-1,55841	
46	847,7062	-0,972	-1	
47	0,0000	-10,000	-1,55841	
48	0,0000	-8,006	-1	
49	0,0000	0,000	-1	

Table 2

Surface no.	K	C1	C2	C3	C4	C5	C6
7	0	3,8786E-09	-1,5770E-13	1,6270E-17	-1,1233E-21	-1,5136E-26	8,5713E-31
13	0	3,8786E-09	-1,5770E-13	1,6270E-17	-1,1233E-21	-1,5136E-26	8,5713E-31
20	0	3,6292E-09	6,7560E-14	5,6841E-19	-6,7883E-23	6,7834E-27	-2,0530E-31
22	0	1,1976E-08	7,3544E-14	7,0329E-19	-1,2632E-23	-3,0105E-27	2,0874E-31
29	0	-8,3929E-09	-3,3961E-13	8,7632E-18	-1,4358E-21	5,5923E-26	2,0181E-30
30	0	1,7409E-08	-1,6961E-13	1,1828E-17	-3,0819E-21	1,7008E-25	-1,6848E-30
35	0	-2,1445E-08	6,7395E-13	-4,8468E-17	5,9926E-21	-2,8763E-25	3,9059E-31
39	0	1,6042E-08	4,7884E-15	2,0832E-16	-2,8771E-20	1,7749E-24	-1,9350E-29
45	0	-6,5639E-08	-8,2521E-12	-1,2733E-16	-1,1662E-20	-1,5813E-23	6,3953E-27

Table 3

51	-242,4305	-34,8290	-1,558410
52	9821,8721	-1,4240	-1,000000
53	-157,8195	-22,5240	-1,558410
54	-257,8030	-1,1080	-1,000000
55	-125,4426	-52,2320	-1,558410
56	-545,5697	-1,2640	-1,000000
57	-182,4345	-19,6850	-1,558410
58	3491,0716	-1,1000	-1,000000
59	0,0000	-10,0000	-1,558410
60	0,0000	-8,0420	-1,000000
61	0,0000	0,0000	-1,000000

Table 3 (cont.)

Surface no.	Radius	Thickness	Index	Reflective
0	0,0000	36,0000	1,000000	
1	0,0000	0,0000	1,000000	
2	333,2125	20,7650	1,558410	
3	3917,6389	94,1110	1,000000	
4	0,0000	0,0000	-1,000000	REFL
5	0,0000	-148,1340	-1,000000	
6	-595,2534	-32,1340	-1,558410	
7	331,1147	-5,4880	-1,000000	
8	312,7988	-10,0000	-1,558410	
9	-682,8537	-300,0000	-1,000000	
10	264,3436	-10,2440	-1,558410	
11	731,0776	-28,2930	-1,000000	
12	191,6338	-10,0480	-1,558410	
13	479,5908	-19,2310	-1,000000	
14	254,9692	19,2310	1,000000	REFL
15	479,5908	10,0480	1,558410	
16	191,6338	28,2930	1,000000	
17	731,0776	10,2440	1,558410	
18	264,3436	300,0000	1,000000	
19	-682,8537	10,0000	1,558410	
20	312,7988	5,4880	1,000000	
21	331,1147	32,1340	1,558410	
22	-595,2534	146,3160	1,000000	
23	0,0000	0,0000	-1,000000	REFL
24	0,0000	-112,8570	-1,000000	
25	-660,9668	-23,0610	-1,558410	
26	556,1870	-10,0000	-1,000000	
27	0,0000	-116,4030	-1,000000	
28	-226,5082	-31,7500	-1,558410	
29	-3414,2334	-25,1180	-1,000000	
30	-3354,8183	-10,0000	-1,558410	
31	-314,6991	-217,5910	-1,000000	
32	-233,5958	-36,8330	-1,558410	
33	960,2043	-32,3470	-1,000000	
34	5805,6084	-10,0020	-1,558410	
35	-240,7709	-42,3390	-1,000000	
36	169,2097	-20,9060	-1,558410	
37	-286,7201	-11,5480	-1,000000	
38	-478,5727	-34,5630	-1,558410	
39	301,8036	-1,0000	-1,000000	
40	-355,1135	-27,7490	-1,558410	
41	1378,0763	-56,2110	-1,000000	
42	-415,3177	-10,0000	-1,558410	
43	-256,9507	-15,2090	-1,000000	
44	-559,7690	-26,8590	-1,558410	
45	479,6752	-10,5000	-1,000000	
46	0,0000	9,4930	-1,000000	
47	-174,1879	-35,5680	-1,558410	
48	-7171,0639	-32,6510	-1,000000	
49	183,6755	-13,5520	-1,558410	
50	255,5654	-2,3140	-1,000000	

Table 4

Surface no.	K	C1	C2	C3	C4	C5	C6
11	0	6,1332E-09	-6,4063E-14	-4,5499E-18	-2,3621E-22	2,4653E-26	-3,8399E-30
17	0	6,1332E-09	-6,4063E-14	-4,5499E-18	-2,3621E-22	2,4653E-26	-3,8399E-30
29	0	3,5716E-09	-2,9481E-13	5,3916E-18	4,4070E-23	5,4581E-27	-7,3136E-31
31	0	-1,8810E-08	2,0385E-13	-1,4483E-18	-5,4964E-22	1,5447E-26	1,0845E-30
35	0	-1,6228E-08	-2,1449E-13	-2,4296E-17	4,2715E-21	-5,4242E-25	3,1678E-29
42	0	1,7399E-08	-7,3701E-13	-3,4088E-17	1,1643E-21	-4,5566E-26	1,2003E-30
47	0	3,9491E-09	-5,1757E-14	-4,2800E-18	6,4019E-22	-1,0309E-25	-7,9826E-30
52	0	-1,7053E-08	8,0221E-13	-8,4651E-17	7,3497E-21	-5,0447E-25	9,0347E-30
57	0	1,3027E-07	4,8555E-12	-2,2801E-15	3,5482E-19	-5,9522E-23	1,5762E-26

Claims

1. A catadioptric projection lens for imaging a pattern situated in an object plane (2) onto an image plane (4) while creating a real intermediate image (3), wherein a catadioptric first section (5) with a concave mirror (6) and a beam-deflecting device (7) is located between said object plane and said image plane and a dioptric second section (8) is arranged following said beam-deflecting device, characterized in that said second section (8) starting after a final reflective surface (9, 10) of said catadioptric section (5) has at least one lens (17) arranged between said final reflective surface (9, 10) and said intermediate image (3).

2. A projection lens according to claim 1, characterized in that said intermediate image (3) is situated in an empty space at a distance from the nearest optical component (17) and/or that said intermediate image (3) is freely accessible.

3. A projection lens according to claim 1 or claim 2, characterized in that said intermediate image (3) is situated at a distance from said final reflective surface (9, 10) of said beam-deflecting device (7), where said distance is chosen such that the diameter of rays incident on a surface orthogonal to the optical axis at the intersection of said final reflective surface (9, 10) with said optical axis (16) is at least 10 % of the diameter of said concave mirror (6) and preferably ranges from 17 % to approximately 20 % of said diameter.

4. A projection lens according to any of the preceding claims, characterized in that positive refractive power is arranged between said final reflective surface (9, 10) and said intermediate image (3).

5. A projection lens according to any of the preceding claims, characterized in that, on its object side, a front lens (17) is inserted ahead of said intermediate image (3) and, on its image side, a rear lens (21) is inserted following said intermediate image (3), and that said lenses are roughly symmetrically arranged with respect to said intermediate image (3) such that asymmetric contributions to imaging aberrations, in particular, coma and/or distortion, by

said lenses (17, 21) due to heating of said lenses are at least partially compensated.

6. A projection lens according to any of the preceding claims, characterized in that the surface of the lens of said second section facing said intermediate image (3) is spherical, wherein preferably the surfaces of both lenses facing said intermediate image (3) are spherical.

7. A projection lens according to any of the preceding claims, characterized in that said catadioptric first section (5) has a magnification of $\beta_M > 0.95$, where same preferably has a magnification greater than unity ($\beta_M > 1$).

8. A projection lens according to any of the preceding claims, characterized in that said catadioptric first section (5) is corrected for spherical aberration such that the longitudinal spherical aberration, SAL, of said first objective assembly (5) satisfies the following condition:
$0 < |SAL/L| < 0.025$, where L is the geometric distance between said object plane (2) and said image plane (4).

9. A projection lens according to any of the preceding claims, characterized in that a intermediate-lens group (41) with at least one lens is arranged in said catadioptric first section (5) between the beamsplitter and a mirror group (12) including said concave mirror (6) and at least one negative lens (13, 14), where said intermediate-lens group (41) preferably includes at least one positive lens (42).

10. A projection lens according to any of the preceding claims, characterized in that said beam-deflecting device (7) has a first mirrored surface (9) for deflecting radiation coming from said object plane (2) to said concave mirror (6) and a second mirrored surface (10), inclined at an angle with respect to said first mirrored surface (9), for deflecting radiation coming from said concave mirror to said second section (8).

11. A projection lens according to any of the preceding claims, characterized in that said beam-deflecting device (7) has only a single mirrored surface (9) that is preferably arranged such that it reflects radiation coming from said concave mirror (6) to said second section (8).

12. A projection lens according to any of claims 1 - 9, characterized in that the final mirrored surface is a polarization-selective mirrored surface, in particular, one that is arranged inside a beamsplitter cube.

13. A projection lens according to any of the preceding claims, characterized in that a lens (11) with a positive refractive power is arranged between said object plane (2) and said beam-deflecting device (7).

14. A projection lens according to any of the preceding claims, characterized in that it has a curved, meniscus-shaped, air space (37) ahead of the system stop (29) and situated close to same.

15. A projection lens according to any of the preceding claims, characterized in that its image side is telecentrically designed and its object side is preferably also telecentrically designed.

16. A projection lens according to any of the preceding claims, characterized in that it is designed for use with ultraviolet light falling within the wavelength range extending from 120 nm to approximately 260 nm, particularly for working wavelengths of approximately 157 nm or approximately 193 nm.

17. A projection illumination system for use in microlithography characterized in that it includes a catadioptric projection lens (1) according to any of the preceding claims.

18. A method for fabricating semiconductor devices, or other types of microdevices, comprising the following steps:
 - providing a mask having a prescribed pattern,

- illuminating said mask with ultraviolet light having a prescribed wavelength, and
- projecting an image of said pattern onto a photosensitive substrate situated in the vicinity of the image plane of a projection lens using a catadioptric projection lens according to any of claims 1 - 16.

Abstract

A catadioptric projection lens configured for imaging a pattern arranged in an object plane (2) onto an image plane (4) while creating a single, real, intermediate image (3) is disclosed. A catadioptric first section (5) having a concave mirror (6), a beam-deflection device (7), and dioptric second section (8) that starts following said beam-deflection device lies between said object plane and said image plane. Said system is configured such that said intermediate image follows the first lens (17) of said dioptric section (8) and is preferably readily accessible. Arranging said intermediate image between a pair of lenses (17, 21) of said dioptric section (8), which follows, and is situated at a large distance from, the final reflective surface (10) of said beam-deflection device (7), helps avoid imaging aberrations.
(cf. Fig. 1).

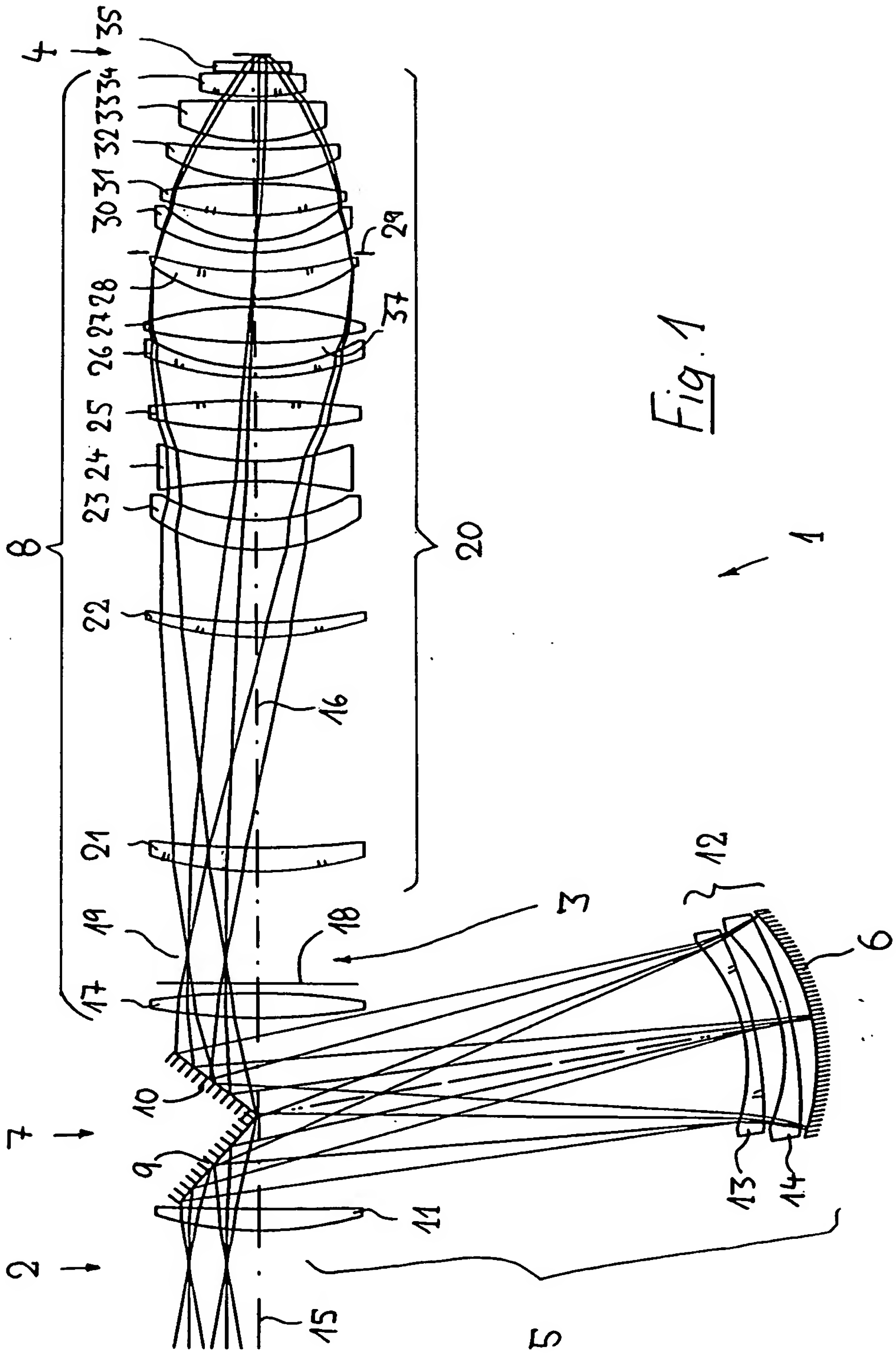
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Fig. 1

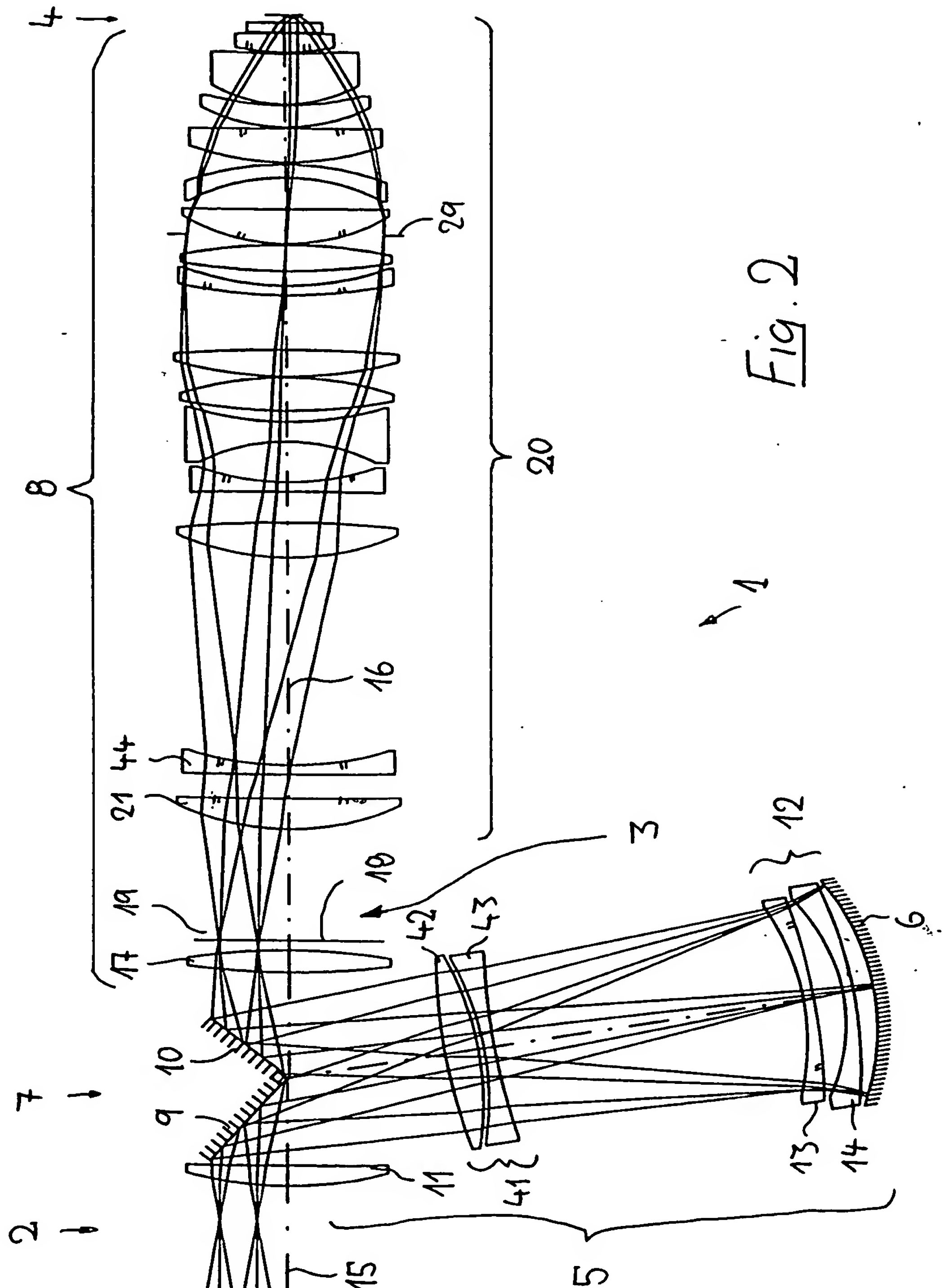

Fig. 2

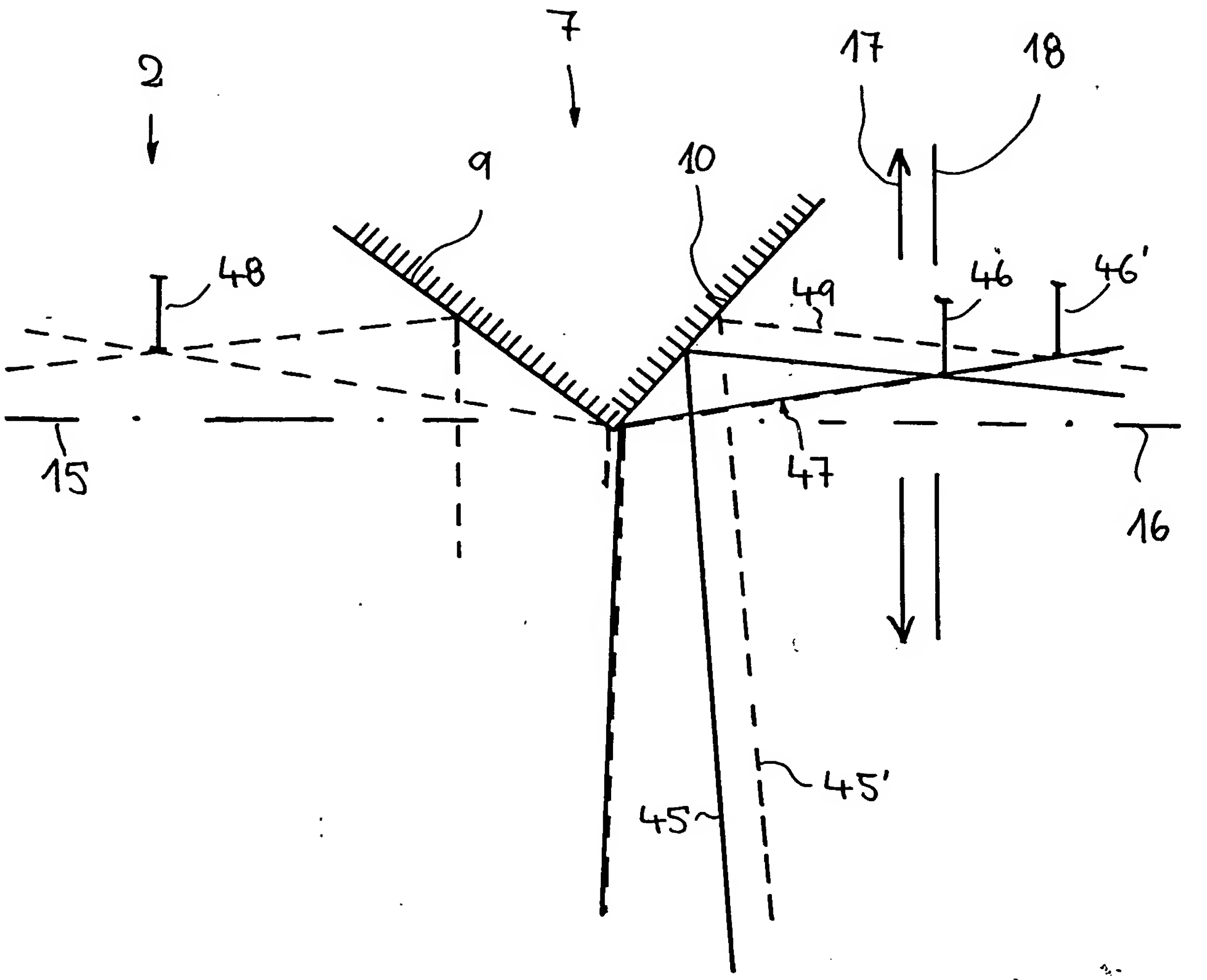

Fig. 3

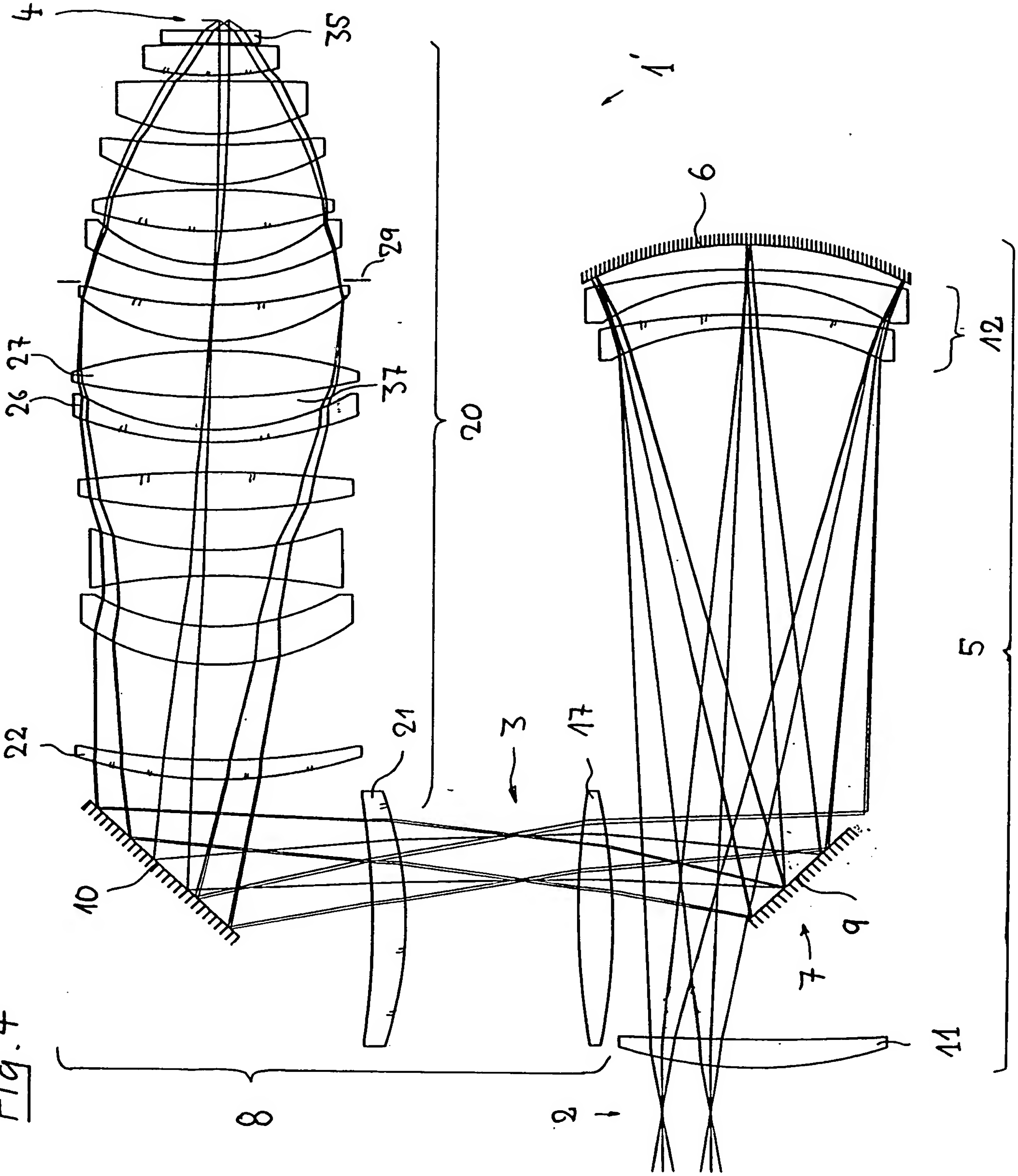

Fig. 4

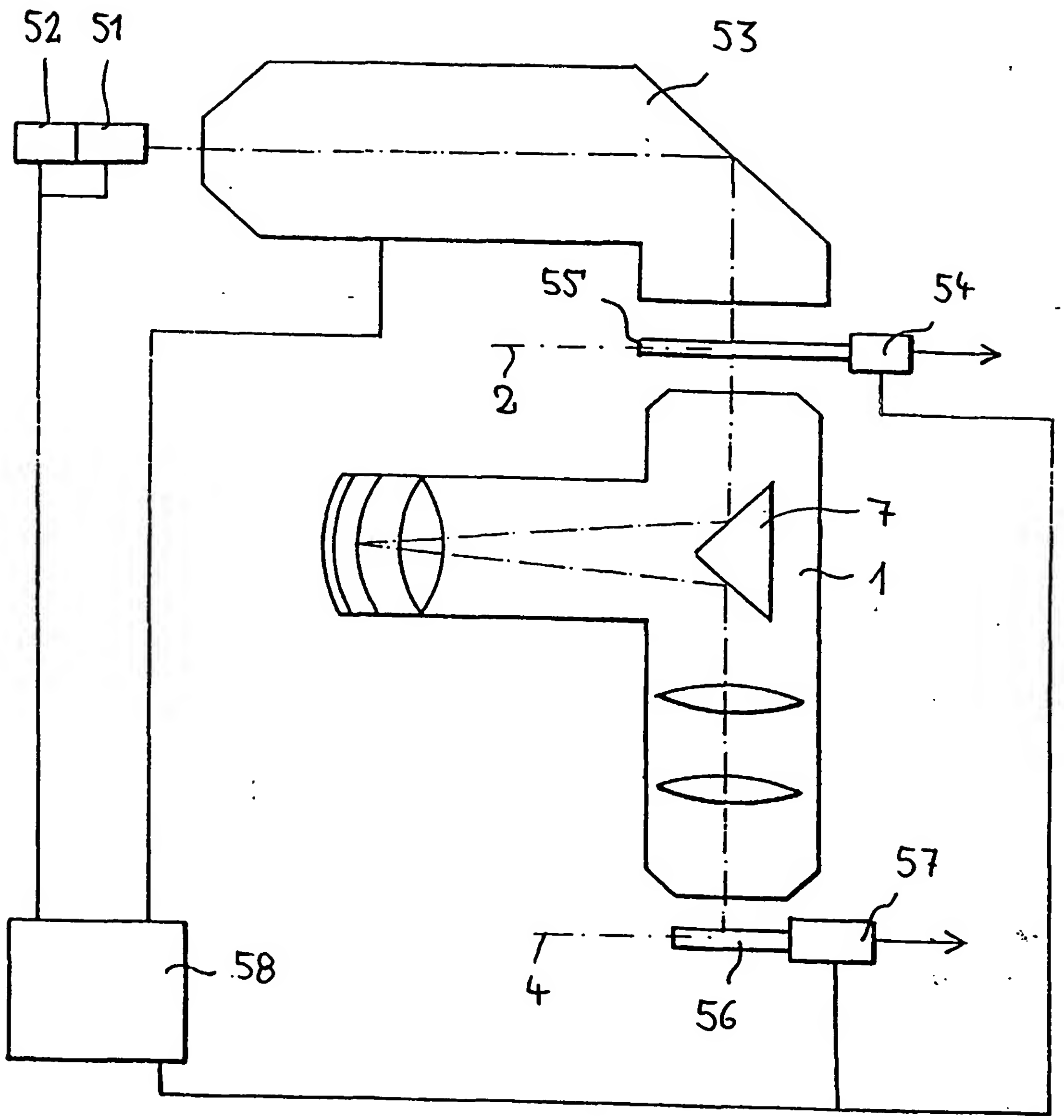

Fig. 5